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E T U O I K E U S T O D I S T U S
P R I O R I T Y D O C U M E N T

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"Procedure for the analysis of physiological signal 2"
(Menetelmä II fysiologisen signaalin analysoimiseksi)

Hakemus on hakemusdiaariin **26.09.2002** tehdyn merkinnän mukaan siirtynyt **Firstbeat Technologies Oy**:lle, **Jyväskylä.**

The application has according to an entry made in the register of patent applications on **26.09.2002** been assigned to **Firstbeat Technologies Oy, Jyväskylä.**

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PROCEDURE FOR THE ANALYSIS OF PHYSIOLOGICAL SIGNAL 2

Inventors: Joni Kettunen, Sami Saalasti
Assignee: Atmosport Oy, Finland

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5,419,338	Sarma
5,810,014	Davis
5,846,206	Bader
5,891,044	Golosarsky
5,902,250	Verrier
5,921,937	Davis
5,941,837	Amano
6,104,947	Heikkilä
6,126,595	Amano
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BACKGROUND OF THE INVENTION

1. Field of the Invention

The present innovation relates to generally to the methods applied in monitoring of physiological functions, in particular to methods that are aimed to describe the physiological state of the human on the basis of ECG and heart period measurement. More specifically, the innovation relates to a procedure of deriving information on the physiological state and a measure of stress of the user on the basis of ambulatory heart beat measurement.

The present innovation describes a procedure of segmenting physical state and deriving a measure of stress from ambulatory heart period signal.

2. Description of the Prior Art

Heart period is among the most commonly used parameters in physiological monitoring. The wide use of heart period is related, on the one hand, to the availability of electrocardiograph (ECG) acquisition device for noninvasive monitoring and, on the other hand, to central role of heart period in the autonomic nervous system function and sensitivity to several physiological states and conditions. Heart period (or, its reciprocal heart rate) forms a basis for different types of analyses and may be defined as the series of intervals between consecutive QRS-waveforms in the ECG-signal. Another method of deriving information on the time distance between consecutive heart beats is the detection of heart beat intervals from heart pulse signal.

The fact that heart period is a complex product of several physiological mechanisms poses a challenge to the use of heart period in applied contexts. This is especially the case within ambulatory measurement, that is, measurement that is performed within natural, free-living condition, outside of controlled laboratory environment and protocols. However, the multidetermined nature of the heart period may also potentate a derivation of additional physiological measures from the heart period signal by means of decomposing heart period into separate components that have a physiological interpretation.

It is well known that both branches of the autonomic nervous system (ANS), the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) influence heart rate. It is commonly known that the activity of the SNS and PNS produce, respectively, an increase and decrease in the heart rate level. It is therefore no surprise that much of the work on assessing physiological functions and states using information on heart beat signal often addresses changes in heart beat as stemming from the influence of SNS and/or PNS. Unfortunately, it is usually very difficult to determine precisely the effects of SNS and PNS on the heart rate, since it is often not apparent which branch of the ANS determines changes in heart rate and, in addition to these mechanisms, there are

several other mechanisms altering the level of heart rate both directly and indirectly, many of which are not well-known.

The prior art has documented several research lines attempting to use heart rate variability (HRV) to quantify more selectively the activity of SNS and PNS. It has been documented that, especially the amplitude of the so-called high frequency (HF) component of the HRV in the frequency region of 0.15–0.50 Hz provides information on the level of parasympathetic outflow to the heart. Unfortunately, although it has been claimed in some instances that the so-called low-frequency (LF) component of the HRV in the frequency region of 0.04-0.15 reflects SNS activity, the effects of SNS on HRV are rather unclear and it is known that several other mechanisms also influence HRV and especially the LF component, including PNS, hormonal responses, metabolic adjustments, and blood pressure control. Thus, increases and decreases in the level of heart rate and HRV may be due to several sources and therefore, it may be only possible to interpret changes in the heart rate level and heart rate variability as being indicative of the activity level of SNS and PNS during controlled situation and preferably with the aid of other measures.

The concept of stress refers generally in physiological domain to a state of heightened level of physiological activity without immediate or apparent requirements for such arousal. In this document, we define a state of stress indicates a body balance wherein the overall activity level, as indicated in, e.g., cardiovascular output, is substantially higher than the level that is required by immediate physical metabolic requirements. The physiological state of stress may be due to different sources, such as, for example, physical load (e.g., posture), physical condition (e.g., fewer), mental stress, or emotional arousal.

Feedback and information on personal stress state and more generally, resources would be very helpful for many individuals to monitor and manage their stress levels, to avoid a state of burnout, and generally to maintain and enhance health condition. Rest and relaxation is an important feature of stress management, as it helps to reduce stress and further buffer against the onset and adverse effects of stress.

It has been well-documented in the scientific literature that a state of stress is associated with heightened SNS influence to the heart and lowered or diminished PNS influence to the heart (e.g., Porges 1992). It is also known in the prior art that, at rest during steady conditions, relaxation is shown as lowered level of cardiovascular activity and in specific, a decrease in the level of heart rate and an increase in the magnitude of the HF component of HRV is often found to associate with state of increased relaxation. Some prior work has been documented to take advantage of the role of HR and HRV in stress and relaxation related phenomena (US Patents 4,832,038; 4,862,361; 5,891,044; 5,941,837; 6,104,947; 6,212,427; 6,358,201).

Despite this correlational relationship, there has been not very much progress in the detection of stress-related physiological states on the basis of heart period signal. There has been some prior work on using information on heart period and HRV to classify user states, in particular in combination with other physiological measures. The prior work based on ECG acquisition has been focused mostly on the determination of clinical condition with special autonomic nervous system tests and is therefore very limited in their application to characterize normal behavioral and physiological states in connection

with, for example, ambulatory measurement (US Patents 5,299,199; 5,419,338; 6,390,986; 6,416,473).

There has been also some documented work on the use of ECG and heart period derived measures to detect certain physiological conditions, wherein typically one or more parameters are monitored and a threshold limit is set to signal a change in state (US Patents 5,267,568; 6,126,595; 6,358,201). These solutions are necessary limited in the content of classifying states and suffer from the fact that the signal value of the heart period and HRV parameters is not always the same but rather, typically varies in combination with physiological states. In another words, they do not account for the state-varying (conditional) relationships between heart period, HRV parameters, and physiological states.

There has been some work on the modeling of state-varying relationships. However, the prior work is typically not related to the determination of stress, may involve heart rate measurement but require the use of two or more physiological measures (US Patents 5,810,014; 5,846,206; 5,902,250; 5,921,937). It is thus clear that, from the point of differentiating different user states and in comparison to the acquisition of only one signal, these approaches require more effort on the measurement of physiological signals and are therefore susceptible to involving more material costs and more restricted end-user protocols. More importantly, the referred work does not include any contribution to the identification of stress and relaxation, wherein the occurrence of physical activity has not been able to take account in the context of using heart beat signal as a single input.

As indicated above, the major problem in the operationalization, measurement and monitoring of stress using information on cardiovascular function, such as acquisition of ECG and heart beat, would be the detection and differentiation of the sources of decreased and increased cardiac function. This is especially evident with increased cardiac activity (e.g., as shown by increased level of heart rate and decreased amplitude of HRV), which may result, for example, from increased state of stress, increased state of physical activity, or postural changes.

OBJECTS AND SUMMARY OF THE INVENTION

The object of the present invention is provide an automatic analysis tool for the purposes of providing information on the physiological state of the user on the basis of ECG or heart period measurement. More specifically, the object of the invention is to provide a procedure for the differentiation of different physiological states and especially to provide a state-detection based method of deriving a measure of stress on the basis of heart period data.

The invention is based on several computational steps wherein the order of the computations has some constraints. The steps may be characterized as follows: (1) initial transformations of ECG and/or heart period signals; (2) segmentation of the heart period data into stationary epochs; (3) detection of the epochs associated with other-than-stress related increases in cardiac activity, including physical exercise, physical activity, recovery from physical activity, and postural change; (4) detection of segments characterized by relaxed state; (5) detection of segments containing a potential stress state; and (6) combining information obtained in steps 3–5 to provide an overall index of stress. The procedure may also contain an initial set-up of parameters wherein some properties of the state detection system are either inputted or determined automatically.

According to the present system, the detection of stress state is based on the following physiological assumptions: There is sympathetic dominance in relationship to the parasympathetic dominance and there is no evidence of physical activity, exercise, movement or posture influenced cardiac reactivity.

The invention may be described as an expert system that consists of a sequence of computations and inferences and provides a novel approach to the detection of physiological states and especially stress on the basis of heart beat signal. The types and methods of giving user feedback are dependent on the purpose of the equipment and software in connection with which the classification and state detection procedure has been applied.

The invention may be applied to and in association with devices such as heart rate monitors and other wearable and mobile computing devices, other types of equipments for physical monitoring and especially involving ECG detection, and software products suited for the analysis of heart period signal. The present invention is useful in combination of any physiological monitoring in the area of monitoring, enhancing and optimizing physiological resources to better manage healthy lifestyle and wellbeing, sports training and fitness, and working capacity. It may be especially useful in the monitoring and providing information on state of stress, where it may be used in the long-term monitoring of the resources.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1. An overall view of the sequences in the procedure.

Figure 2. Initial transformations of the ECG and heart period signal.

Figure 3. An illustration of the procedure for the detection of exercise, recovery from exercise, physical activity, movement and postural changes.

Figure 4. Procedure for the detection of relaxation, stress state, and combination of information to describe overall body resources.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

INTRODUCTION

The innovation is described here with the aid of an example implementation. It should be noted that the described system is not bound to any specific model or specifications, but rather, different alterations, forms, and improvements are possible and are in line with the spirit of the innovation. Thus, the following merely contains a description of the preferred embodiments of the innovation.

The system involves initially an estimation, input, or use of previous values to characterize individual parameter values that influence the detection of states within the system. This estimation of the values is optional for the system. The values may be estimated by using formulas based on empirical data and user-inputted values, such as age, weight, height, and sex. The values may be also based on history values based on empirical physiological measurements, or they may be inputted by the user or expert. Examples of values that may be used on this context are maximum and minimum levels of oxygen consumption, heart rate level, or HRV level.

Figure 2 shows an overview of the initial transformations of the ECG and heart period signal. The ECG-signal is transformed into consecutive R-R intervals by using sequential QRS-complexes as markers of the beginning and end of a R-R interval. Also other components of the ECG signal may be used to detect the R-R interval. The consecutive R-R intervals are scanned through an artifact detection filter to perform an initial correction of falsely detected, missed, and premature heart beats. Another potential methods of deriving information on the intervals between consecutive heart beats would be based on the detection of intervals from pulse signal on the basis of different detection algorithms. It should be therefore noted, that in principle, the present innovation applies to all domains wherein temporal information is obtained on the timings between consecutive heart beats.

Consecutive artifact-corrected R-R intervals are transformed into equidistant heart period time series by using a weighted linear interpolation of the R-R intervals. For example, a time domain sampling rate of 5 Hz may be used.

Initial features that may be used in the segmentation of the physiological process of the user into stationary epochs are computed prior to the segmentation. The features may include several different components, including the following: spectral power (ms^2) in the LF and HF frequency regions, information on respiratory period and ventilation as derived, for example, from the heart period according to Kettunen & Saalasti (Patent pending, FIN 20025029), variation and inconsistencies in respiratory parameters, and oxygen consumption as derived from, for example, heart period and heart period derived respiratory period or ventilation. If available, also external measures of physical activity

may be used as a component for segmenting the physiological processes into stationary epochs. All these measures are computed on a continuous basis with preset or dynamically alternating window sizes, thus potentiating the capability for real-time use.

A univariate or multivariate set of features is combined to segment the physiological processes into stationary epochs. In another words, the target of the present procedure is to divide segments wherein the properties of the physiological system are similar and consistent within-the-segment, using the information obtained from the derived physiological features. An example of a algorithm to perform this is the so-called generalized likelihood ratio test, which basically performs the minimization of the variance within the segments and maximization of the variance between the (consecutive) segments. This process is controlled by threshold parameters that determine the sensitivity of the segmentation process. The use of multivariate set of parameters describing user state is recommended to gain more stability and reliability to the segmentation of data into stationary epochs.

The generalized likelihood ratio test is classically applied to model selection but it is also adapted to segmentation algorithms, e.g. the one presented by Fancourt and Principe. In this embodiment the function used to estimate the signal in the segment is median. The error is calculated from the mean absolute error between the median and the signal within segment. For closer details of the algorithm see the article by Fancourt et al.

In the following the procedure for detecting physiological state is presented. Selected physiological parameters are analyzed from each stationary segment to form a basis for inference on states that include increased cardiac activity. The detection of physically (i.e., metabolism related) induced states of increased cardiac reactivity is excluded before the detection of potential states and intensities of relaxation and stress. Figure 3 presents a flowchart on the procedure of detecting physical activity related states.

Increased level of cardiac activity (e.g., increased heart rate level or decreased heart period level) may be due to the process of recovering from physical exercise or from any physical activity. The state of recovering from exercise may be detected by, for example, applying the method described in Saalasti, Kettunen, Pulkkinen (A procedure for predicting body fatigue during exercise and recovery from exercise on the basis of physiological measurement. Patent pending, FIN 2002) to determine the level of recovery requirements in the body and classify segments involving recovery demands higher than a certain predetermined threshold as recovery state.

The system requires information on the intensity of physical activity and exercise to differentiate exercise related effects on cardiac system from, e.g., stress related effects. The transformation of heart beat level into proportional intensity of physical activity, applying for example information on the relationship of heart rate level to oxygen consumption. It is possible also to use information on initial parameters, such as maximum and minimum levels of heart rate and oxygen consumption to increase the accuracy of determining the intensity of physical activity. However, it is clear that the direct transformation of heart level to exercise intensity does not produce optimal results for the purposes of differentiating other than exercise related increase in cardiac activity from exercise induced reactivity.

The estimate of the proportional intensity of physical activity may be enhanced by including information on the ventilation, as obtained, e.g., from heart period. Furthermore, given that exercise has also certain pattern of changes in respiratory activity (e.g., exercise is associated with increased respiration, whereas other-than-exercise related cardiac reactivity is not often associated with similar respiratory reactivity) and HRV (e.g., a certain level of HRV is typically associated with certain level of heart rate during exercise), and temporal length (i.e., exercise and intensive physical activity is necessarily bound to have a certain temporal length). It would be also possible to use external sensors to detect the occurrence and intensity of movement and physical activity with, for example, accelerometer or skin temperature sensors, to support the determination of exercise intensity.

A certain threshold value is preset to determine whether a certain segment involves exercise or intensive physical exercise. Given that no other reasons related to respiration, HRV, or temporal length of increased heart rate provides evidence that a potential exercise induced increase in cardiac activity is not associated with intensive physical activity, segments containing a mean intensity of physical activity higher than, for example, 50% of exercise intensity may be classified as intensive exercise.

Movements, start-up of a physical activity, and postural changes have all metabolic requirements and also increase heart rate level. It is thus necessary to differentiate these effects from other, non-metabolic factors influencing cardiac activity. It is known that PNS often controls increase in cardiac activity at the onset of movement and decrease in cardiac activity at the end of movement. It is also known that standing up, which poses a so-called orthostatic reaction, is associated with increase in the spectral power in the LF frequency region of HRV in relationship to HF power, which usually decreases when standing up. Based on these assumptions, a covariance parameter according to Equation 1 has been derived to index movement related changes in cardiac activity.

Equation 1

$$movement = \alpha \cdot \mathrm{cov}(\log(HFpow)) + E\left(\frac{LFpow}{HFpow}\right)$$

An increase in the level of the described parameter indicates the prevalence of movement related increases in cardiac activity and thus may be used to differentiate states of movement, onset and offset of physical activity, and postural changes.

The detection of light physical activity is similar to that of intensive physical activity but the threshold values are different. However, the detection of light physical activity differs from that of detecting intensive physical activity in that it is expected that metabolic demands related changes in cardiac activity are associated with light physical activity. In another words, the covariance term introduced in Equation 1 is used to differentiate light physical activity related increases in metabolism from cardiac reactivity that is due to different sources. It is also here of note that, in a similar manner to the intensive physical activity, additional sensors detection movement could be also used to differentiate segments that include physical activity.

The detection of movement and reactivity due to changes in posture is performed by using the covariance term presented in Equation 1 with preset threshold values and a period

surrounding the covariance. The covariance term may be smoothed with, for example, a Hanning window.

In general, it is known that exercise, physical activity, and movement all have their typical time frames that have minimal temporal requirements for recovery. For this purposes, it may be possible to use a frequency or time domain measure to provide information on the temporal properties of the changes in cardiac activity, thus potentiating the comparison of those with those typical in the case of different types of physical activity.

It is important to notice that, as for example, the changes on the heart beat during physical activity are associated with several different types of changes, these changes may be combined in an automatic decision function that may be, for example, deterministic, heuristic, or based on multivariate methods such as fuzzy systems and neural network.

Figure 4 shows an overall view on the detection of relaxation and stress. Relaxation index for the segment is determined by the combination of heart period and HF power as illustrated in Equation 2.

Equation 2

$$relax\_threshold = \frac{HR\max - HR\min}{10} + HR\min$$

$$relax\_index(segment) = \frac{\sum_{t=segment\_start}^{t=segment\_end} \sqrt{\frac{HFpow(t)}{HR(t)}}}{segment\_length}$$

The relaxation may be detected for example by calculating mean heart rate in the segment and then using a threshold proportional to minimum and maximum heart rate. An example is presented in Equation 2. If mean heart rate is less than the threshold the segment may be detected as relaxation.

If no relaxation state is detected, the data segment is a potential candidate of including stress. Equation 3 shows an example of how an index of stress may be computed. In Equation 3, *HR* denotes heart rate level, *CT* denotes inconsistencies in the frequency distribution of HRV due to changes in respiratory period, or alternatively, variability in the respiratory signal. *HFpow* and *LFpow* denote spectral powers in the HF and LF regions of the HRV, respectively.

Equation 3

$$stress\_index(segment) = \frac{\sum_{t=segment\_start}^{t=segment\_end} \frac{HR(t)\cdot CT(t)}{\log(HFpow(t))\cdot\log(LFpow(t))}}{segment\_length}$$

Of course, both indices shown in Equations 2 and 3 are only illustrative and different forms may freely apply. Both indices may be also used to derive continuous parameters,

which may be useful in some contexts of deriving overall, long-time information on stress and relaxation.

It should be clear to anyone familiar with the field that the formula presented for computing stress index is only illustrative and may be formed in several methods. The principle is to search for periods of increased heart rate with other markers of potential stress and related in general to heightened level of SNS activity and diminished level of PNS activity.

The indices of relaxation and stress may be combined taking advantage of the proportion of different states and the intensity of relaxation and stress states. An example of such combination is presented in Equation 4.

Equation 4

$$total = \frac{(T - T_R)}{T} \cdot (1 - RLXpow/100) + c \cdot \frac{T_S}{T} \cdot STRpow,$$

where c is a constant, T is total time of the measurement, T_R is time classified as relaxation, T_S is time classified as stress, $RLXpow$ the intensity of relaxation in percentages and $STRpow$ is the intensity of stress state (see the computation of stress index in Equation 3). The intensities may be calculated via mean or median values of the corresponding time series indices. The combined index may be especially useful in the comparison of different days.

In principle, a segment is identified as stress if heart rate is constantly at a high level and it is apparent that it is caused by lowered level of PNS, higher level of SNS, and there is no evidence of physically determined heart rate reactivity. In fact, given that stress is associated with a tonic low level of PNS and that high level of PNS potentiates reactivity, the absence of PNS mediated responses is also an indicator of stress and may be taken more formally into account. If a person is highly stressed, it may not be possible to find states of relaxation even during long periods.

Feedback on the results of the present procedure may be presented to the user either on real-time application or off-line, after the measurement. It is possible to give feedback on states, on relaxation and stress components, and overall resources. The feedback may be given in many forms, for example, in graphics or as a single parameter that is easy to interpret.

2 2

Claims

What is claimed is:

1. A procedure of segmenting heart beat signal into physiological states, characterized by at least one of the following
   a. A method for the segmentation of the heart beat signal into internally coherent segments
   b. The use of at least one analysis method for the identification of segments that include increased metabolic rate due to exercise, physical activity, movement, or postural changes, including methods such as, for example,
      i. Information on the co occurrence of heart beat changes and HRV measures, such as the moving covariance presented in the preferred embodiments
      ii. Information on the HRV and any component of it, such as, for example, LF and HF components
      iii. Exercise intensity, such as that based on the transformation of heart beat level and/or information on respiratory period into level of oxygen consumption
      iv. Recovery from exercise
      v. Respiratory period or ventilation in combination with heart rate level and/or HRV or its decomposition
      vi. The use of the information on the temporal properties of the exercise, physical activity, and movement as characterized by, for example, frequency or time domain methods
      vii. The use and combination of information as obtained from several detection

2. A procedure according to Claim 1, which is used to identify states and periods of exercise, physical activity, movement, or postural changes from heart period signal

3. A procedure for the detection of stress and resources, characterized by a procedure according to Claim 1 and combining the procedure of Claim 1 to the information derived on the basis of heart beat data, based on, for example,
   a. Heart beat level
   b. Derivation of index or measures of stress based on information obtained from the heart beat
   c. Derivation of index or measures of relaxation based on information obtained from the heart beat
   d. Derivation of index or measures of resources based on information obtained from the heart beat

4. A procedure for the computation of overall index of stress, relaxation and resources, characterized by the procedure according to Claim 3 and by the computation of an index that represents a summary of the existence and level of stress, relaxation and resources for a period of measurement, such as a 3 hours, half day or full day

5. A system for measuring stress and relaxation on the basis of heart period measurement, wherein information on the length of detected relaxation and length of detected stress is used as informative in the detection and quantification of relaxation and stress states

6. A system for measuring stress and/or relaxation on the basis of heart period measurement, wherein the measure of stress and/or relaxation is computed for a segmented period of heart period

7. A system according to the Claims 1 5, wherein information on the exercise level, physical activity, movement, or postural changes is obtained from heart beat and/or one or more sensors detecting movement, such as accelerometer

8. A system according to claims 1 3, which is used for correcting heart rate based oxygen and energy consumption estimate

ABSTRACT

The present innovation is a procedure for the segmentation and classification of the user's state and for the determination of a measure of stress on the basis of ambulatory measurement of heart beat. The procedure may be described as an expert system that is based on several computational steps. The system provides information for the automatic detection and differentiation of movement from other sources of cardiac reactivity and performs a detection of states with the capability of functioning in ambulatory conditions wherein heart beat measurement often contains complex components. The core of the innovation is the differentiation of the source of increased cardiac activity between the stress and physical activity induced accelerative changes in the cardiac function. The information obtained from the classification of physiological state may be used as a starting point in analysis of ambulatory ECG or heart beat information and directly to provide the user simple feedback on the physiological state and especially on a physiological state of stress. The procedure has wide spread use in the ambulatory monitoring of physiological signals and states, and especially as related to the devices aimed at providing feedback on users health and wellbeing.

2 · 4

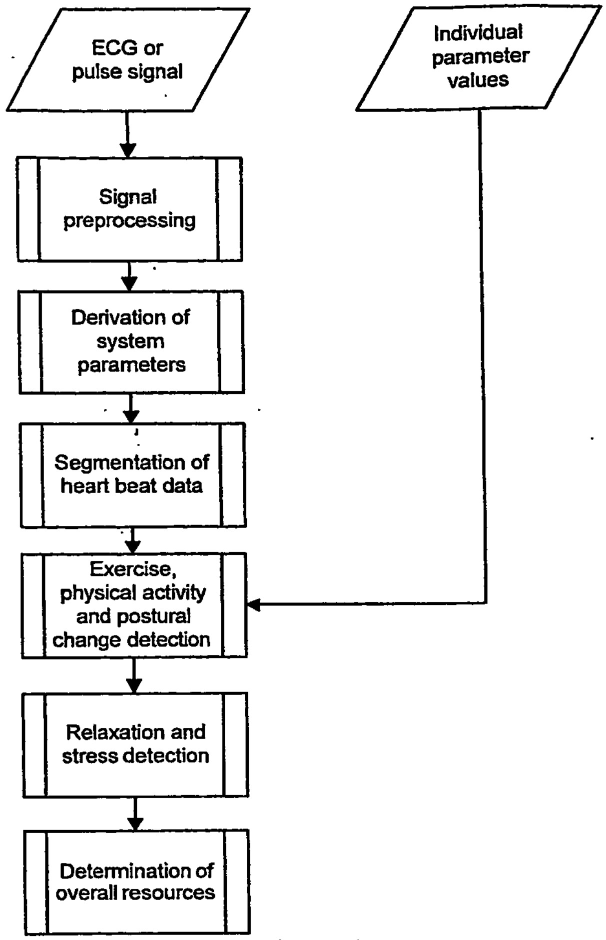
ECG or pulse signal
Individual parameter values
Signal preprocessing
Derivation of system parameters
Segmentation of heart beat data
Exercise, physical activity and postural change detection
Relaxation and stress detection
Determination of overall resources

Figure 1

2/4

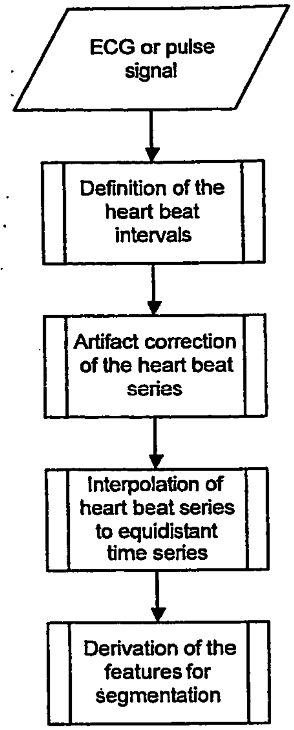
ECG or pulse signal
Definition of the heart beat intervals
Artifact correction of the heart beat series
Interpolation of heart beat series to equidistant time series
Derivation of the features for segmentation

Figure 2

24

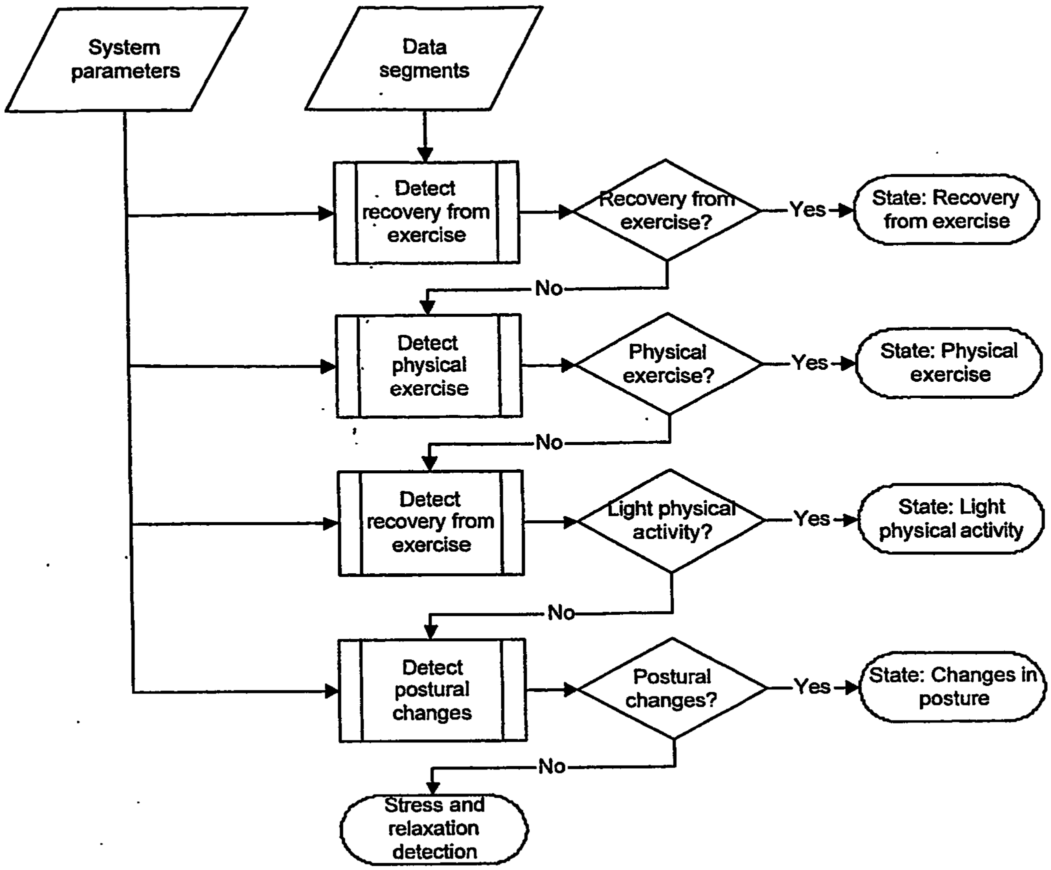
System parameters
Data segments
Detect recovery from exercise
Recovery from exercise?
Yes
State: Recovery from exercise
No
Detect physical exercise
Physical exercise?
Yes
State: Physical exercise
No
Detect recovery from exercise
Light physical activity?
Yes
State: Light physical activity
No
Detect postural changes
Postural changes?
Yes
State: Changes in posture
No
Stress and relaxation detection

Figure 3

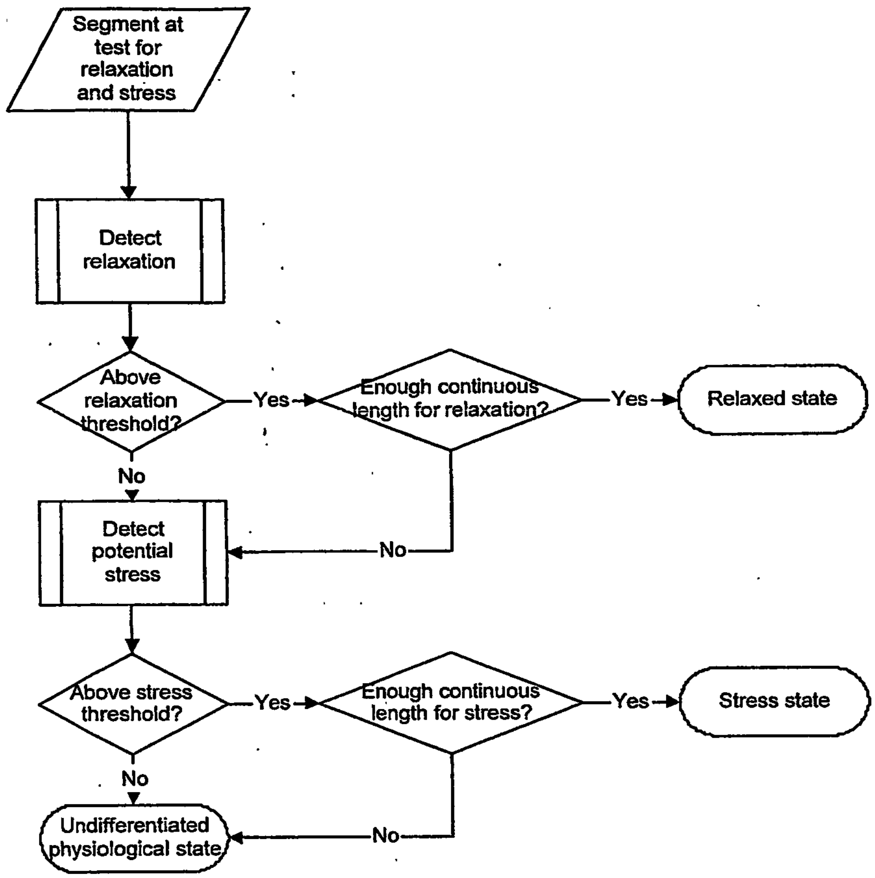
Segment at test for relaxation and stress
Detect relaxation
Above relaxation threshold?
Yes
Enough continuous length for relaxation?
Yes
Relaxed state
No
Detect potential stress
No
Above stress threshold?
Yes
Enough continuous length for stress?
Yes
Stress state
No
Undifferentiated physiological state
No

Figure 4